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Innovation on the seed market: the role of IPRs and commercialisation rules

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Abstract

This article deals with the impact of legislation in the seed sector on incentives for variety creation. The first category of rules consists in intellectual property rights and is intended to address a problem of sequential innovation and R&D investments. The second category concerns commercial rules that are intended to correct a problem of adverse selection. We propose a dynamic model of market equilibrium with vertical product differentiation that enables us to take into account the economic consequences of imposing either Plant Breeders' Rights (PBRs) or patents as IPRs and either compulsory registration or minimum standards as commercialisation rules. The main result is that the combination of minimum standards and PBRs (patents) provides higher incentives for sequential and initial innovation and may be preferred by a public regulator when sunk investment costs are low (high) and the probability of R&D success is sufficiently high (low).

Keywords: Intellectual Property Rights, Plant Breeders' Rights, Catalogue, Product differentiation, Seed market, Biodiversity

JEL classifications: D43, K11, L13, Q12, Q16

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1 Introduction

Since the early twentieth century, public authorities have been very active/keen to set up instruments that aim at preserving and enhancing the diversity of plants and seeds used in the agricultural sector. Such diversity is seen as a public good (non rivalry and non excludability) subject to underinvestment due to the non-cooperative behaviour of private agents in the sector (see Polasky and al., 2005, for a review of biodiversity's economic aspects). The use of different varieties of the same plant by neighbourhood farmers may, for instance, limit the risk of spreading of plant diseases to the whole community of farmers. Two complementary types of instruments have been set up: Intellectual Property Rights (IPRs) and seeds commercialisation rules. Yet, the existing literature has never dealt with them simultaneously. Therefore, little is known about the respective merits of the different combinations of instruments. This article aims at filling the gap and, more specifically, it focuses on the contrasted solutions adopted in the United States and in Europe.

The rationale for defining intellectual property rights for plant varieties is that anthropic intervention is essential to obtain new varieties, thanks to seed selection, for instance. Such interventions are costly and may thus be rewarded to occur as the outcome of research and development activity of rational economic agents (Scotchmer, 2004). Though this general idea is widely acknowledged and is part of the international agreement on Trade-Related aspects of Intellectual Property Rights (TRIPS), whether *sui generis* IPRs or patents have to be used is controversial. Partisans of *sui generis* IPRs argue that inventions in the seed sector are essentially incremental/cumulative and that a "research exemption" enabling breeders to freely develop new varieties from protected varieties created by others is required to efficiently promote innovation and biodiversity. Cumulative innovation was discussed by Scotchmer (1991) who gives an overview of the main related issues and O'Donoghue et al. (1998) highlight problems arising from the length and breadth of a patent in a context of cumulative inventions. The European Union has set up specific Plant Breeders' Rights (PBRs) also known as Plant Variety Rights (PVRs) or Plant Variety Protection (PVP) from the International Union for the Protection of

New Varieties of Plants (UPOV) convention[1], granted to the breeder of a new variety of plant and that give him exclusive control over its marketing and use for a predefined number of years. This specific IPRs system provides the research exemption described above. Partisans of patents, and among them the United States, contest the fact that new plant varieties have to be treated as specific inventions[2]. IPRs in agricultural biotechnology are discussed by Lesser (1999, 2000), Louwaars et al. (2005), Trommetter (2008). Ramanna and Smale (2004) and Ramanna (2006) focus on the particular IPRs system on plant variety in India. So far, the economic literature on PBRs has mainly focused on the empirical assessment of the effectiveness of incentives to innovate generated by intellectual property rights in the seed sector. No definitive conclusions can be drawn from this literature. Like Alston and Venner (2002), Carew and Devadoss (2003) attempt to test whether yields have been significantly increased by PBRs for respectively wheat in the United States and canola in Canada. They find no significant impact. In contrast, Diez (2002) scrutinises the role of PBRs in Spain and concludes in favour of a positive impact. Lesser (1997) and Srinivasan (2003, 2012) assess the value of PBRs, Srinivasan (2003) with the aim of evaluating farmers' rights in India. Ambec et al. (2008) and Perrin and Fulginiti (2008) examine the Coase conjecture with different assumptions concerning the behaviour of farmers and breeders and market conditions. Lence et al. (2005) develop a theoretical model with three possible equilibria to look at the impact of the appropriability level. More generally, literature lacks discussions of the respective merits of patents and PBRs for stimulating innovation in the seed sector. Noticeable exceptions are Moschini and Yerokhin (2008) and Yerokhin and Moschini (2008) who find that when research cost is high, PBRs is not the best option. Bessen and Maskin (2009) and Nagaoka and Aoki (2009) look at "innovation imitation" which is quite similar to research exemption, however they do not really compare PBRs and Patents. This article is an attempt to fill a gap in existing literature.

Divergence across countries about the relevant IPRs overlaps divergence regarding the second type of instrument; seed commercialisation rules. Commercialisation rules are specifically designed to ad-

[1]The UPOV promotes PBRs as IPRs on plants, at the time of writing there are 72 signatories of the UPOV convention. The convention can be found at `http://www.upov.int/upovlex/en/upov_convention.html`, last accessed July 2014

[2]However, the US have also a PBRs system but only for sexually reproduced plants.

dress the adverse selection problem that arises in the seed market (Akerlof, 1970). When faced with the opportunity to buy seeds of a new plant variety or of an old plant variety that is not widely grown, farmers need a credible assessment of the characteristics of the variety. In the absence of such a credible assessment, they would not accept to pay different prices for differentiated seeds and the eviction of "high quality" varieties by "low quality" varieties would occur. Without the opportunity to buy seeds that better fit their needs, farmers would then incur a loss in terms of yields and profitability. Addressing the adverse selection problem in the seed market thus not only matters for the promotion of biodiversity but is also important in boosting agricultural production. Instruments set up to circumvent the problem of adverse selection generally consist of regulatory approval based on the fulfilment of minimum standards by commercialised seeds. How stringent these minimum standards are greatly depends on the country. In European Union, the registration in the catalogue is mandatory and relies on the Distinctness Uniformity and Stability (DUS) and Value for Cultivation and Use (VCU) tests carried out by the authority competent for granting Plant Breeders' Rights or by separate institutions, such as public research institutes, acting on behalf of that authority. Commercialisation approval is thus tightly linked to Plant Breeders' Right in the European Union. By contrast, commercialisation rules in the United States rely on less stringent criteria and, last but not least, it is not tight to the grant of a patent on the commercialised variety (see Tripp and Louwaars, 1997, for a description of the regulation of the seed market for some countries). As a result, a "free seed" movement has developed in Europe to stress that the way Plants Breeders Rights are coupled with commercialisation rules is counterproductive to the promotion of biodiversity, or even contest the principle of property rights. The key idea is that landrace varieties contributing to biodiversity can not be commercialised because they do not fulfil one or several of the three DUS criteria. The debate in Europe is thus bipolarised with opponents to current commercialisation rules and/or property rights on the one side and partisans (mainly large firms from the seed industry) of the current coupled system of PBRs and DUS based commercialisation rules on the other side. This article tries to highlight the debate from an academic perspective. Indeed, little has been said from an academic economist's point of view about what combination of commercialisation rules and IPRs should be preferred and which economic agents could gain or lose from a switch in the current system to this combination, if different from the current system.

Section 2 then proposes a theoretical model to analyse the optimal combination of commercialisation rules and IPRs for the seed market. It starts with an adaptation to the seed market of the vertical differentiation model proposed by Prescott and Visscher (1977) and used by Bresnahan (1987) to describe the US car market, the advantage of which being that a dynamic approach of market equilibrium is used. Plant varieties are assumed to result from a sequence of incremental inventions. The type of IPRs that are set up by public authorities is assumed to affect market structure and thus influences the decision to proceed or not with an incremental invention at each period. Section 3 introduces biodiversity as a public good, the level of which modifies the productivity parameter of agricultural land and thus the demand for the different varieties of seeds. Numerical simulations based on calibration of the model are examined. Section 4 presents a dynamic framework of the theoretical model where combinations of commercialisation rules and intellectual property rights are compared both in terms of incentives to innovate and in terms of welfare for different levels of R&D costs and R&D probability of success for obtaining a new variety. Section 5 concludes.

2 The seed market in a static framework

Though innovation is intrinsically a dynamic process, we first attempt to develop a static analysis of the seed market. The underlying idea is that the market structure is influenced by the type of IPRs that prevails for plant varieties. Therefore, prior considering the dynamic effects of IPRs on innovation, we have to determine their static effects. For this purpose, we adapt a standard market equilibrium model with vertical differentiation to our problem. We first characterise the demand addressed by heterogenous farmers to different varieties of seeds for a same crop. We then turn to the analysis of the supply side. We distinguish between a landrace variety and "breeder" varieties. "Breeder" varieties are supplied and created by breeders whereas the landrace already exists. Suppliers of the landrace variety have no market power whereas breeders of created varieties have a market power that crucially depends on the type of IPRs that prevail for plant varieties. In addition to the distinction between a patent regime and PBRs, we furthermore examine the impact of opting for minimum standards or a catalogue for regulating the commercialisation of seeds.

2.1 Farmers behaviour

We consider farmers growing the same crop by means of three different types of input: land L, seeds S and a vector Z of other inputs including capital and labor. We more specifically consider the nested production function

$$Y = A \; Min \left[\alpha S; \beta L; \gamma f(Z)\right] \epsilon_i \tag{1}$$

where Y stands for the output level, $f(Z)$ is a sub-production function with constant returns to scale and ϵ_i is a random term with mean μ_i and standard deviation σ_i. The underlying idea is that seeds land and the whole set of other inputs are perfect complements but that substitution between other inputs (namely capital and labour) is possible. A is a productivity parameter, the value of which may depend on a measure of biodiversity assumed to be exogenous for the time being. The random term ε_i captures the fact that the variety i of crop grown affects both the average production level and its variability. The random profit level $\widetilde{\pi}_i$ for a farmer that chooses variety i with a unit price of seeds w_i may be expressed as

$$\widetilde{\pi}_i = P \; A \; \alpha \; S \; \varepsilon_i - \delta_i \; S \tag{2}$$

where $\delta_i = w_i + w_z \; \alpha/\gamma$ and w_z is the minimum cost at which elements of the vector Z of variable inputs may be combined to obtain the efficient aggregate level $f(Z) = S \; \alpha/\gamma$ associated to a given quantity of seeds S. Land is treated as a fixed input so that its price does not appear in the expression of the profit level. If land was a variable input with unit price w_L, then $w_L\alpha/\beta$ would have to be added to δ_i. The profit level is expressed in terms of S rather than in terms of L or Z in order to focus on the demand of seeds.

Farmers are assumed to have a constant relative risk aversion index in the sense that the risk premium they associate to their random profit level $\widetilde{\pi}_i$ is proportional to the surface of land they use and, as a direct consequence of perfect complementarity between land and seeds, to the quantity of seeds they buy. In order to capture this attitude toward risk, the mean-standard deviation version of Markowitz's criteria is used (Markowitz, 1952). Accordingly, the risk adjusted profit level of a farmer choosing variety i of the crop is given by

$$\pi_i = (P\ A\ \alpha\ S\ \mu_i - \delta_i\ S) - \theta\,(P\ A\ \alpha\ S\ \sigma_i) \tag{3}$$

where θ is a risk aversion parameter and $\theta\,(P\ A\ \alpha\ S\ \sigma_i)$ is the risk premium. Note that farmers are assumed to choose the same variety for the whole surface area they use. Allocation of different plots of land to different varieties is not considered. A reason for this may be, for instance, that such a mix implies too high organisational costs. In order to analyse the optimal choice of variety, it is more specifically convenient to rewrite the risk adjusted profit level in the following form

$$\pi_i = S\,(A\ P\ \alpha\ \ (\mu_i - \theta\ \sigma_i) - \delta_i) \tag{4}$$

Thereafter, varieties are indexed according to their rank once sorted according to the mean value of the random component ϵ_i in the production function, corrected to take account of risk aversion (i.e. $i > j \Leftrightarrow \mu_i - \theta\ \sigma_i > \mu_j - \theta\ \sigma_j$). Furthermore, it is assumed that there are two kinds of seeds. The first type is variety $i = 0$ referred to as the landrace variety, i.e. a variety that has been used since long ago and generates the lowest per unit of seed expected value of production with the highest risk (i.e. $\mu_0 < \mu_i\ \forall i > 0$ and $\sigma_0 > \sigma_i\ \forall i > 0$). The second type of seeds gathers all other varieties and is referred to as the "breeder" type. Varieties of the "breeder" type have to pass an uniformity and stability test that aims to provide a guarantee that production will not vary due to heterogeneity among seeds of a same variety. For these varieties, the risk affecting production is thus limited to meteorological conditions and is thus assumed to be of the same magnitude for all of them (i.e. $\sigma_i = \sigma$ $\forall i > 0$). As a result, "breeders" varieties are differentiated only in terms of their value of μ_i that may be thought of as a quality parameter. Farmers are heterogeneous in terms of the productivity of their land measured by parameter A. Under these additional assumptions, the optimal choice of variety for farmers is formally identical to the optimal choice of quality by consumers in example 4 of Prescott and Visscher (1977). More specifically, the linear utility function of consumers with a heterogeneous marginal rate of substitution is replaced by the risk adjusted profit level which is linear with respect of parameter A that captures heterogeneity among farmers. Farmers prefer variety i to variety j if and only if $\pi_i > \pi_j$. This inequality yields

$$\begin{array}{lll} A > \frac{\delta_i - \delta_j}{P\ \alpha\ ((\mu_i - \theta\ \sigma_i) - (\mu_j - \theta\ \sigma_j))} & \text{if} & i > j \\ A < \frac{\delta_i - \delta_j}{P\ \alpha\ ((\mu_i - \theta\ \sigma_i) - (\mu_j - \theta\ \sigma_j))} & \text{if} & i < j \end{array} \tag{5}$$

Farmers who choose variety i among a set $\{0, \cdots, I\}$ of varieties of a same crop are thus farmers with a productivity parameter A of land that satisfies

$$\begin{array}{ccccccc} \frac{\delta_0}{P\ \alpha\ \eta_0} & < & A & < & \frac{\delta_1 - \delta_0}{P\ \alpha\ (\eta_1 - \eta_0)} & \text{for} & i = 0 \\ \frac{\delta_i - \delta_{i-1}}{P\ \alpha\ (\eta_i - \eta_{i-1})} & < & A & < & \frac{\delta_{i+1} - \delta_i}{P\ \alpha\ (\eta_{i+1} - \eta_i)} & \text{for} & 0 < i < N \\ \frac{\delta_i - \delta_{i-1}}{P\ \alpha\ (\eta_i - \eta_{i-1})} & < & A & & & \text{for} & i = N \end{array} \tag{6}$$

with $\eta_i = \mu_i - \theta\ \sigma_i$ and $\eta_j = \mu_j - \theta\ \sigma_j$. The left hand side threshold for $i = 0$ follows the condition that farmers decide to grow variety $i = 0$ of the crop if and only if they make a positive risk adjusted profit with that variety. If this condition of a positive risk adjusted profit is satisfied for $i = 0$ then it is also satisfied when farmers prefer a variety $i > 0$ because this choice implies that they reach a higher level of risk adjusted profit.

For the problem to make sense, it is expected that the minimum costs δ_i ($i \in \{0, \cdots, I\}$) per unit of seed are consistent with a positive demand for each variety. Therefore, we assume that $A_{\max} >$

$(\delta_N - \delta_{N-1}) / (P\ \alpha\ (\eta_N - \eta_{N-1}))$ (i.e. there is a positive demand for variety $i = N$) and that $A_{\min} < (\delta_1 - \delta_0) / (P\ \alpha\ (\eta_1 - \eta_0))$ (i.e. there is a positive demand for variety $i = 0$). We also introduce the simplifying assumption that production is profitable for all farmers. For this purpose, assumption $A_{\min} > \delta_0 / (P\ \alpha\ \eta_0)$ is added. It guaranties that farmers with the lowest productivity can make profits at least by choosing variety $i = 0$. Farmers may also be heterogeneous as regard seeds S they use but their distribution in terms of S is supposed to be independent of their distribution in terms of A. Given these assumptions and the fact that $\delta_i = w_i + w_z\ \alpha/\gamma$ for all varieties, the demand system for the different varieties may be expressed in terms of their prices w_i ($i \in \{0, \cdots, I\}$) as follows

$$q_i = \begin{cases} \overline{q}\left(\frac{w_1 - w_0}{P\ \alpha\ (\eta_1 - \eta_0)} - A_{\min}\right) & \text{for} \quad i = 0 \\ \overline{q}\left(\frac{w_{i+1} - w_i}{P\ \alpha\ (\eta_{i+1} - \eta_i)} - \frac{w_i - w_{i-1}}{P\ \alpha\ (\eta_i - \eta_{i-1})}\right) & \text{for} \quad 0 < i < N \\ \overline{q}\left(A_{\max} - \frac{w_i - w_{i-1}}{P\ \alpha\ (\eta_i - \eta_{i-1})}\right) & \text{for} \quad i = N \end{cases} \tag{7}$$

with $\overline{q} = M\overline{L}\frac{1}{\alpha}/A_{\max} - A_{\min}$ where M is the number of farmers and $\overline{L}$ the average surface they use[3]. $M\ \overline{L}\frac{1}{\alpha}$ is a measure of market size for seeds.

2.2 Breeders behavior

In a static framework, the behaviour of breeders of created varieties is crucially influenced by the type of IPRs that prevails for plant varieties and that shapes the structure of the seed market. We argue that a patent regime is associated with either a monopolistic-monovariety structure or a monopolistic-multivariety structure on the breeders side, whereas a PBRs regime more or less leads to an oligopolistic market structure. Seeds for the landrace variety just have to be produced at a constant unit cost c_0, which implies that they are supplied in a competitive context and are priced at their constant unit cost. We examine and compare pricing under the two IPRs regimes and also discuss the incidence of switch from minimum standards to a catalogue for commercialisation rules on the seed market.

[3]The way the average surface appears in the demand system directly follows on from the simplifying assumption that the distribution of surface and productivity are independent.

2.2.1 Pricing with a patent system

For ease of presentation, we start with the case of a patent system to protect plant varieties. It is necessary to remember that varieties of the "breeder" type are ranked according to the increasing value of the quality parameter μ_i. The implicit assumption is that the development of "breeder" type varieties begins with variety $i = 1$ and proceeds variety by variety from i to $i + 1$ up to variety $i = N$ with the highest quality level. In this sense, varieties $i > 1$ are incremental inventions developed from the initial invention $i = 1$. Since patents convey an exclusivity right on all incremental inventions that may be derived from an initial invention, we consider that the inventor of variety $i = 1$ has *de facto* a monopolistic position on all other varieties[4]. For a given number N of developed varieties, the objective of the initial inventor is to maximise the joint profit of supplying all varieties

$$\underset{\{w_i,\cdots,w_N\}}{\text{Max}} \sum_{i=1}^{N} (w_i - c_i) q_i \tag{8}$$

where c_i stands for the constant unit cost of producing seeds for variety i. The corresponding first order conditions for $i \in \{i, \ldots, N-1\}$ may be written as

$$\begin{aligned} w_i =& \frac{c_i}{2} + \frac{w_{i+1}}{2} \frac{\eta_i - \eta_{i-1}}{\eta_{i+1} - \eta_{i-1}} + \frac{w_{i-1}}{2} \frac{\eta_{i+1} - \eta_i}{\eta_{i+1} - \eta_{i-1}} \\ &+ \left(\frac{w_{i+1} - c_{i+1}}{2} \right) \frac{\eta_i - \eta_{i-1}}{\eta_{i+1} - \eta_{i-1}} + \left(\frac{w_{i-1} - c_{i-1}}{2} \right) \frac{\eta_{i+1} - \eta_i}{\eta_{i+1} - \eta_{i-1}} \end{aligned} \tag{9}$$

Note that for $i = 1$ we have $w_{i-1} = c_0$ so that the last term vanishes. For $i = N$, the first order condition is

$$w_N = P\,\alpha \frac{\eta_N - \eta_{N-1}}{2} A_{\max} + \frac{c_N}{2} + \frac{w_{N-1}}{2} + \frac{w_{N-1} - c_{N-1}}{2} \tag{10}$$

This set of first order conditions is linear with respect to the unknown prices w_i $(i \in \{1, \ldots, N\})$

[4] If the production of incremental varieties is licensed to other firms then the inventor of the initial variety is assumed to extract the rent of the licensee so that he formally behaves as if he was in a monopolistic position.

so that it is expected that one and only one solution exists. In order to determine this solution, we re-express (9) and (10) in terms of the threshold values of the productivity parameter involved in (6). Let A_{i-1}^{i} denote the threshold value $\frac{w_i - w_{i-1}}{P\alpha\ (\eta_i - \eta_{i-1})}$ of the productivity parameter A above which a farmer prefers variety i to variety $i-1$. Then, (9) and (10) simplify to

$$A_{i-1}^{i} = \frac{A_{\max}}{2} + \frac{1}{2} \frac{c_i - c_{i-1}}{P\ \alpha\ (\eta_i - \eta_{i-1})} \quad \forall i \in \{1, \ldots, N\} \tag{11}$$

that directly yields the optimal expression of each threshold. According to (11), a monopolistic pricing implies that the value of thresholds remain unchanged when the total number of varieties increases. It follows on from this first result and from the demand system (7) that the equilibrium quantity sold for each variety is not affected by an incremental invention taking the form of a new variety with a higher value of parameter η except for the breeder variety prior to the new breeder variety due to truncated demand resulting from the arrival of the latest variety. Furthermore, the equation (11) enables us to determine a necessary and sufficient condition for the monopolist to supply each of the varieties $i \in \{1, ..., N\}$ in order to maximise its total profit.

Proposition 1 *A monopolist breeder optimally supplies each of varieties $i \in \{1, ..., N\}$ if and only if the sequence $\{c_i, \eta_i\}$ of unit costs and quality indexes forms a convex curve in space $\{c, \eta\}$.*

Proof 1 *According to equation 11 and to the demand system 7, a positive demand is addressed to each variety $i \in \{1, ..., N\}$ if and only if $\frac{c_i - c_{i-1}}{\eta_i - \eta_{i-1}}$ increases with i, which is equivalent to the stated convexity property.*

Under the condition stated in Proposition 1 and using the expression $\frac{w_i - w_{i-1}}{P\ \alpha\ (\eta_i - \eta_{i-1})}$ of threshold A_{n-1}^{n}, we conclude that prices are defined by the following recursive formula for a monopolist:

$$w_i = w_{i-1} + A_{i-1}^{i} P\ \alpha\ (\eta_i - \eta_{i-1}) \quad \forall i \in \{1, \ldots, N\} \tag{12}$$

Given that $w_0 = c_0$ because multiple suppliers of the landrace variety compete under perfect competition, formula (12) yields the following optimal value of prices:

$$w_i = c_0 + \frac{A_{\max}}{2} P \ \alpha \ (\eta_i - \eta_0) + \frac{1}{2} \ (c_i - c_0) \quad \forall i \in \{1, \ldots, N\} \tag{13}$$

Formula (13) is a key element in stating the Proposition 2

Proposition 2 *Equilibrium prices for varieties optimally supplied by a multi-product monopolist are unaffected by an incremental invention.*

Proof 2 *The result follows on from the fact that,according to 13, the equilibrium price for a variety only depends on its unit cost and technical characteristics and on that of the landrace variety.*

Conversely, Proposition 3 yields a necessary and sufficient condition for a monopolist breeder to supply only the highest quality.

Proposition 3 *A monopolist breeder optimally supplies the sole highest quality variety $i = N$ if and only if the sequence $\{c_i, \eta_i\}$ of unit costs and quality indexes forms a concave curve in space $\{c, \eta\}$.*

Proof 3 *According to equation 11 and to the demand system 7, a positive demand is addressed to variety $i = N$ whereas no positive demand is addressed to varieties $i \in \{1, ..., N-1\}$ if and only if $\frac{c_i - c_{i-1}}{\eta_i - \eta_{i-1}}$ decreases with i, which is equivalent to the stated concavity property.*

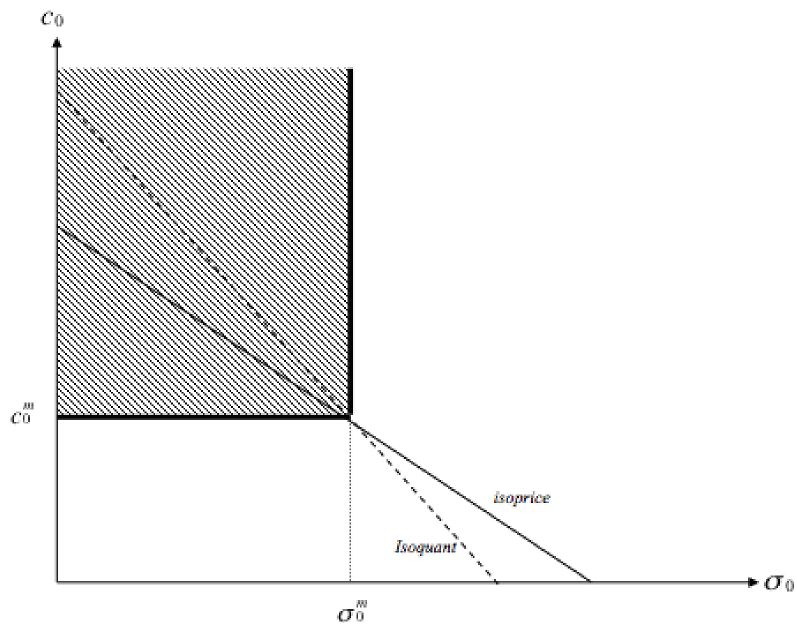
Under the condition stated in Proposition 3, the formula (10) with η_0 in place of η_{N-1} and c_0 in place of c_{N-1} directly yields the optimal price w_N. We then deduce the following Proposition.

Proposition 4 *The optimal price w_N of the highest quality variety of seeds for a monoproduct monopolist is identical to the optimal price of the same variety chosen by a multiproduct monopolist breeder that would optimally supply all varieties $i \in \{1, ..., N-1\}$.*

Proof 4 *Replacing η_{N-1} by η_0 and c_{N-1} by c_0 in formula (10) and rearranging yields the same optimal price for variety N than the one obtained with equation (13).*

As will be emphasised later in the article, Propositions 2 and 4 play a crucial role in analysing and comparing prices under a patent regime versus PBRs, at least when $N = 2$.

Figure 1: Impact of a switch from minimum standards to the catalogue



In order to determine the impact of choosing either minimum standards or a catalogue as commercial rules, we draw the isoprice and isoquant curves for a given variety i in space $\{\sigma_0, c_0\}$. Indeed, the key difference between minimum standards and a catalogue is that, in the event of a catalogue, seeds of the landrace variety have to pass the same DUS test than seeds created by breeders. Therefore, the standard deviation σ_0 characterising the random component affecting the profit of farmers that use the landrace has to be lowered to the same level than that of farmers that use breeders' varieties. This implies a higher unit cost c_0 for seeds of the landrace variety. Whether the breeder is a monoproduct monopolist or a multiproduct monopolist does not matter for isoprice curves because the optimal price is formally given by the same equation (13) whatever the variety i considered. Moreover, one easily checks that these curves are linear and decreasing in space $\{\sigma_0, c_0\}$ and move upwards when they are associated to a higher price. Starting from $\sigma_0 = \sigma_0^m$ and $c_0 = c_0^m$ with minimum standards, the adoption of a catalogue induces a move somewhere inside the hatched area in Figure 1. If a small decrease of σ_0 is enough to pass the DUS test as required for registration in a catalogue and this decrease results in a sufficiently high additional unit cost for the landrace variety $i = 0$, then the combination $\{\sigma_0^c, c_0^c\}$ associated with a catalogue will be above the initial isoprice curve and the prices of varieties $i \in \{1, ..., N\}$ supplied by the monopolist breeder will increase. An opposite result is obtained if σ_0^c is small compared to σ_0^m whereas c_0^c is close to c_0^m. If the breeder is a monoproduct monopolist, the quantity q_N of variety N optimally supplied is

$$q_N = \overline{q}\left(\frac{A_{\max}}{2} - \frac{1}{2P}\frac{c_N - c_0}{\alpha\left(\mu_N - \mu_0\right) - \theta\left(\sigma_N - \sigma_0\right)}\right) \tag{14}$$

Then, the isoquant is also linear and decreasing in space $\{\sigma_0, c_0\}$ and move upwards when associated to a higher quantity. Thus, the consequence for the optimal supply of variety N of a switch from minimum standards to a catalogue are similar to those already obtained for the price of variety N. Whether the isoquant is higher than the isoprice (as represented in Figure 1) or not is unclear. Nevertheless, combining variations of the price and of the quantity, we conclude that the profit generated by variety N will increase (respectively decrease) if σ_0^c is close to (respectively far from) σ_0^m and c_0^c is far from (respectively close to) c_0^m. If the breeder is a multiproduct monopolist, then the analysis for the quantity q_N of the highest quality variety is formally identical to that for the monoproduct monopolist. The analysis for lower quality varieties is simpler because the corresponding optimal quantities q_i $i \in \{1, ..., N-1\}$ are invariant with respect to σ_0 and c_0.The sign of the variation of the associated profits is thus identical to the sign of the variation for the corresponding optimal prices. All these results are summarised in Proposition 5.

Proposition 5 *Under a patent regime, if the switch from minimum standards to a catalogue results in a small drop of σ_0 but a sharp increase of c_0, then prices, and the markup, of all the varieties that a monopolist breeder will find optimal to supply and the associated profits will increase. The optimal* *quantity of the highest quality variety will also increase whereas the quantities of lower quality optimally supplied, if any, will remain unchanged.*

Proof 5 *See Figure 1 and the comments above.*

According to Proposition 5, it is thus expected that, under a patent regime, breeders will argue in favour of the catalogue rule rather than in favour of minimum standards only if they think that the additional unit cost incurred by suppliers of seeds for landraces to meet the DUS criteria is high enough compared to the resulting reduction of productivity uncertainty that affects farmers. We now turn to the case of a PBRs regime.

2.2.2 Pricing with a PBRs system

Due to the research exemption, we consider that with a PBRs system each variety is created by a different firm so that the market structure for seeds is oligopolistic. Of course, it may happen that a same firm creates several varieties, an eventuality that we do not take into account for two reasons. First, we want to stress the difference between PBRs and patents in terms of market structure and market equilibrium. Second, in the dynamic framework introduced later in the paper, we focus on a two-period analysis where only a monopolistic or a duopolistic market structure may arise. In an oligopolistic framework, prices are obtained as the outcome of a Bertand Nash game in prices. For a given number N of developed varieties, the objective of each breeder i is to maximise his own profit v_i of supplying variety i given prices of all other varieties:

$$\underset{w_i}{\text{Max}}(w_i - c_i)q_i \tag{15}$$

The corresponding first order condition is

$$w_i = \frac{c_i}{2} + \frac{w_{i+1}}{2}\frac{\eta_i - \eta_{i-1}}{\eta_{i+1} - \eta_{i-1}} + \frac{w_{i-1}}{2}\frac{\eta_{i+1} - \eta_i}{\eta_{i+1} - \eta_{i-1}} \tag{16}$$

for $i \in \{i, \dots, N-1\}$ and

$$w_N = P\,\alpha \frac{\eta_N - \eta_{N-1}}{2} A_{\max} + \frac{c_N}{2} + \frac{w_{N-1}}{2} \tag{17}$$

for $i = N$. (16) and (17) define the reaction functions characterising the game in prices. The linearity of theses reaction functions guarantees that if a solution exists it is unique. Nevertheless, it seems that it is not possible to rearrange this set of reaction functions in terms of the sole thresholds A^i_{i-1}. It is thus expected that, contrary to what happens in the monopolistic context, both prices and the values of thresholds vary when the total number of varieties increases. Note also that, according to (16) and (17) and the fact that $\eta_i > \eta_{i-1}$ $\forall i \in \{1, ..., N\}$, reaction functions have a positive slope. We thus obtain the following characteristic of the game in prices:

Proposition 6 *There is strategic complementarity between prices.*

Proof 6 *Reaction functions are increasing with respect to strategic decisions of other players which defines strategic complementarity.*

Proposition 6 is a key element for the graphical comparison of monopolistic and oligopolistic pricing when $N = 2$.

As in the case of a patent regime, isoprice and isoquant curves are useful to highlight the consequences of adopting either minimum standards or a catalogue for commercialisation rules. Nevertheless, we focus here on the case where $N = 2$ because we are not able to find a simple analytical expression of optimal prices for a generic value of N. Proposition summarises the results as regards the consequences of a change in commercialisation rules.

Proposition 7 *If the corresponding change in the unit cost c_0 and the standard deviation σ_0 of productivity are of limited magnitude and the variation of σ_0 is small enough compared to the variation of c_0, then the strengthening of commercial rules resulting from a switch from minimum standards to a catalogue induces an increase of the price of breeders' varieties and an increase of the quantities of seeds sold to famers for these varieties.*

Proof 7 *See Appendix A.*

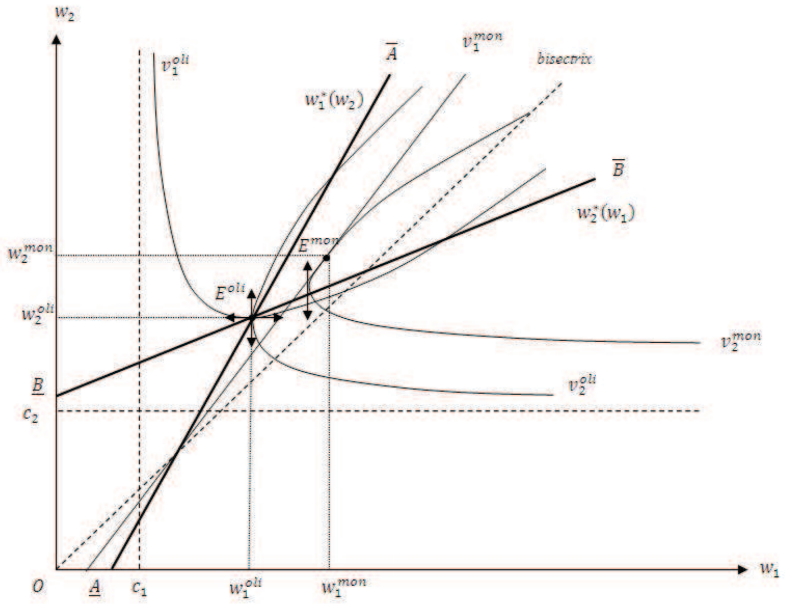
In spite of the similitude between Propositions 5 and 7, these two Propositions neither mean that the change in prices and quantities under a PBR regime and under a patent regime will have the same magnitude, nor that it will have the same sign. This is expected to happen only in the polar cases where the variation of σ_0 is small compared to that of c_0 (prices and quantities of breeders' varieties then increase) or where the variation of σ_0 is high compared to that of c_0 (prices and quantities of breeders' varieties then decrease).

2.2.3 Comparative analysis of pricing

Although a standard result in economics states that, for a single product, the markup of a monopolist is higher than that for any other market structure, it is not that obvious to extend it to a multiproduct context. Indeed, it is not intuitively unconceivable that in order to maximise its total profit a multiproduct monopolist optimally chooses to charge a higher price for the high quality good but a lower price for low quality goods, for instance. Moreover, when the monopolist optimally decides to supply the sole highest quality good, the demand system is substantially affected and the comparison of prices is complicated. Therefore, it is worth providing some analytical results as regards the comparison of optimal prices with an oligopolistic versus monopolistic market structure. The focus is on the case of two breeder varieties. The reason for this is that in the dynamic framework that is analysed latter in the paper, R&D investments have to be analysed backwards and the model is limited to two periods for computational tractability so that $N = 2$ at the best.

Figure 2 illustrates the Bertrand-Nash equilibrium of the price game in the second period when two different firms have an exclusivity right on each variety of the "breeder" type. Such a market structure may arise only under a PBR regime.The dark line $\left(\underline{A}\overline{A}\right)$ represents the reaction function $w_1^*(w_2)$ of the firm providing variety 1. The expression of this reaction function solves the first order condition (16) for $i = 1$. One easily checks that, due to the assumption $\eta_i > \eta_{i-1}$ $\forall i \in \{1, ..., N\}$, the slope

Figure 2: Bertrand-Nash equilibrium with N=2



of the reaction function $w_1^*(w_2)$ in space $\{w_1, w_2\}$ exceeds unity. By construction, isoprofit curves for firm 1 admit their minimum in space $\{w_1, w_2\}$ at the crossing point with the reaction function $w_1^*(w_2)$. They decrease (respectively increase) with w_1 for all values of w_1 lower (respectively higher) than this minimum. They all admit $w_1 = c_1$ as an asymptote when w_2 tends to infinity Similarly, the dark line $(\underline{B}\overline{B})$ represents the reaction function $w_2^*(w_1)$ of the firm providing variety 2 and its expression solves the first order condition (17) for $N = 2$. The slope of the reaction function $w_2^*(w_1)$ in space $\{w_1, w_2\}$ amounts to $\frac{1}{2}$. By construction, isoprofit curves for firm 2 admit their minimum in space $\{w_2, w_1\}$ at the crossing point with the reaction function $w_2^*(w_1)$. They decrease (respectively increase) with w_2 for all values of w_2 lower (respectively higher) than this minimum and admit $w_2 = c_2$ as a horizontal asymptote in space $\{w_1, w_2\}$. Finally, isoprofit curves for both firms are associated with higher profit levels as they shift further from the origin. The oligopolistic equilibrium for the prices of varieties $i = 1$ and $i = 2$ is characterised by the coordinates $w_1 = w_1^{oli}$ and $w_2 = w_2^{oli}$ of the intersection E^{oli} of the two reaction functions if and only if the intersection lies above the bisectrix in space $\{w_1, w_2\}$. Otherwise the demand for variety $i = 1$ as defined in (7) would generate a negative value, thus indicating that variety $i = 1$ would actually be abandoned. Profit levels at point E^{oli} for firm 1 and firm 2 are respectively denoted v_1^{oli} and v_2^{oli}.

Some indications on the relative position in Figure 2 of optimal prices for a multiproduct monopolist when $N = 2$, compared to the oligopolistic price equilibrium, may also be obtained. Indeed, a standard result of the maximisation program (8) of the sum of profits for $N = 2$ is that the unique interior solution to first order conditions (16) and (17) is a point of tangency between isoprofit curves of varieties 1 and 2. Such a tangency may be obtained only on subsets of Figure 2 where isoprofit curves for both firms are either decreasing or increasing in space $\{w_1, w_2\}$. According to the previous discussion about the general shape of isocurves, we know that isoprofit curves for variety 1 are decreasing in space $\{w_1, w_2\}$ above the line associated to the reaction function $w_1^*(w_2)$ and are increasing behind the same line whereas isoprofit curves for variety 2 are decreasing in space $\{w_1, w_2\}$ behind the line associated to the reaction function $w_2^*(w_1)$ and are increasing above this line. Thus a point of tangency between isoprofit curves may be found only inside the area $O\underline{A}E^{oli}\underline{B}$ or inside the cone $\overline{B}E^{oli}\overline{A}$. Inside the area $O\underline{A}E^{oli}\underline{B}$ isoprofit curves are associated with a lower profit level than at point E^{oli} for both varieties of crops. A monopolist would then be better off choosing E^{oli} rather than such a tangency point. The solution for monopolistic pricing can thus only belong to the cone $\overline{B}E^{oli}\overline{A}$ where isoprofit curves are associated with higher profit levels for both varieties. Moreover, for a monopolist to supply variety 1 it is required that w_2 exceeds w_1 so that the equilibrium point E^{mon} (with coordinates $w_1 = w_1^{mon}$ and $w_2 = w_2^{mon}$ and profit levels v_1^{mon} and v_2^{mon}) lies above the bisectrix. Note that according to (12) this condition is fulfilled if the technical condition $\eta_i \geqslant \eta_{i-1}$ $\forall i \in \{1, ..., N\}$ and the cost condition $c_i \geqslant c_{i-1}$ $\forall i \in \{1, ..., N\}$ are satisfied (one of the two inequalities being strict for each i). We can then write the following Proposition:

Proposition 8 *The optimal price charged by a monopolist for a variety, whether it optimally chooses to be monoproduct or it rather opts for multiproduction, is always higher than the price of the variety when each variety is supplied by a different breeder.*

Proof 8 *The result directly follows from the analysis of Figure 2 and Proposition 4.*

The point in Proposition 8 is that the result does not only applies to the case of a multiproduct monopolist but also to the case of a monoproduct monopolist.

3 The effects of endogenous biodiversity

Biodiversity is often seen as a natural protection of crops against risks of a massive attack by predators or as a natural mean for crops to adapt to environmental change (see e.g. Polasky and al., 2005; Altieri, 1999). Nevertheless underinvestment in the preservation and development of biodiversity is also often stressed. Such an underinvestment may be thought off as the outcome of a "tragedy of the commons". Indeed, efforts to preserve and develop biodiversity on his own fields by a farmer do not only benefit to himself but also to the neighbouring farmers. The existence of this spillover effect implies that a farmer can not fully internalize the benefits that accrue from his efforts and symmetrically for his neighbours. Biodiversity is thus a common resource for which each farmer is subject to a lack of incentives in terms of preservation and development efforts. Endogenous biodiversity is dealt with in this section by slightly modifying the specification of the model presented in the previous section.

3.1 Biodiversity as a common resource

In order to tackle with the endogeneity of biodiversity and with its positive external effects, it is assumed that the productivity parameter A introduced in the production function (1) linearly depends on a measure *bio* of biodiversity:

$$A = \overline{A} + \lambda bio \tag{18}$$

where $\overline{A}$ is an heterogeneous component that varies from a farmer to an other one and λ is a constant parameter. $\overline{A}$ reflects the minimum productivity level that would be obtained in the absence of biodiversity and λbio is the part of productivity to be attributed to biodiversity. We assume that $\overline{A}$ is uniformly distributed on the interval $[\overline{A}_{\min}, \overline{A}_{\max}]$ so that A is also uniformly distributed on an interval

$[A_{\min}, A_{\max}]$ with $A_{\min} = \overline{A}_{\min} + \lambda bio$ and $A_{\max} = \overline{A}_{\max} + \lambda bio$. A direct and convenient consequence of this specification is that the derivation of the demand system and market equilibrium for a given level *bio* of biodiversity is similar to that presented in the previous section. What makes the model different is that most usual biodiversity measures depend on the number of varieties and possibly on the quantity of each variety that is effectively grown. The level of biodiversity is then endogenous and *bio* has to be found as a fixed point of the model. Unfortunately the demand system and equilibrium prices conditional on the level of *bio* are highly nonlinear with respect to this biodiversity measurement so that we are not able to find the corresponding fixed point analytically. The problem is compounded by the fact that commonly used measures of biodiversity are themselves highly nonlinear expressions of the quantities of crops of the different varieties. We more specifically consider three different index of biodiversity:

The first and simplest way to measure biodiversity is to count the number N of varieties effectively grown at a given period of time. Note that for a variety to be taken into account it is required that it is not only supplied but also effectively bought and grown by farmers. Put another way, N is not the total number of varieties listed in a catalogue but the total number of varieties effectively found in fields (Baumgärtner, 2006). Even this simple measurement of biodiversity is endogenous because firms at the two periods of the model can decide to invest in R&D and create a new variety or not. It is expected, for instance, that above some threshold of the sunk R&D cost K, firms prefer not to invest. The second way to capture biodiversity is to use is the Simpson index defined as

$$D = \sum_{i=0}^{N} g_i^2 \tag{19}$$

where g_i is the share of variety i in the total quantity of seeds bought[5]. D reflects the probability that two randomly selected units of land are cultivated with the same variety. It is actually more convenient to use the index of diversity E defined as $1 - D$. Indeed, E goes to zero when biodiversity decreases and is bounded by one as biodiversity is very high, which is more consistent with the way

[5]Due to the perfect complementarity between seeds and land, this is also the share of total land allocated to variety i.

biodiversity is assumed to affect the production function (1) through the productivity parameter defined in (18). The third way to measure biodiversity is to compute the Shannon-Wiener index derived from the concept of entropy

$$H = -\sum_{i=0}^{N} g_i * \ln(g_i) \tag{20}$$

with, by convention, $g_i * \ln(g_i) = 0$ for $g_i = 0$. Again, it is convenient to introduce a normalisation of this index known as the Pielou index

$$P = \frac{H}{\ln(N)} \tag{21}$$

When $P = 1$, each variety has exactly the same share of the total land cultivated and biodiversity is at its maximum. When biodiversity is very low, P tends to zero.

In further section, the Simpson index of diversity is chosen for two reason: it is similar to the Herfindahl and Hirschmann Index (HHI), commonly used in industrial economics to measure market concentration, and it facilitates the search of a fixed point needed to calibrate the model.

3.2 Model calibration

For the purpose of assessing the impact of endogenous biodiversity on market equilibrium, a numerical calibration of the model is needed. This calibration enables us to find a fixed point for the market shares given the biodiversity feedback effect on productivity. Parameters numerical values are shown in Table 1, they all correspond to the case of wheat in France. They were worked out using data from *Groupement National Interprofessionnel des Semences* (GNIS), from the *Farm Accountancy Data Network* (FADN) and from *Banque de France*. FADN provides average data on the agricultural sector of the European Union, and the GNIS on the seed sector. In addition, the GNIS performs tests to certify seeds.

In order to calculate the first (constant) part of A_{min} and A_{max} we use the variation of yield by

Table 1: Parameters

P	19€/q	μ_0	1
L_{mean}	14.42	μ_1	1.04
$M_{farmers}$	356,070	μ_2	1.08
$c_0 standards$	31.25€/q	$\sigma_0 standards$	0.2
$c_0 catalogue$	40.56€/q	σ_i	0.18
c_i	49.85€/q	λ	13
A_{min}	$20 + \lambda bio$	$c_z * \alpha/\gamma$	722
A_{max}	$110 + \lambda bio$	θ	0.25

hectare of wheat in different populations of farmers available on FADN. The second part enables us to take into account biodiversity. λ was set to a value that makes the impact of biodiversity significant (it amounts to about 20% of the global productivity for the median farmer in our simulations, under the assumption of uniform distribution for parameter A). Data for the unit cost c_0^m of farm-saved seeds with minimum standards, for the unit cost c_0^m of farm-saved seeds with a catalogue and for the unit cost c_i for certified seeds were collected from GNIS. On the basis of information provided by experts from the *Institut National de la Recherche Agronomique* (INRA), the unit cost c_i incurred to produce breeders varieties is assumed to be invariant with respect to the quality index $\eta_i = \mu_i - \theta\ \sigma_i$ of seeds. Consequently, the sequence of unit costs $\{c_i\}$ is concave with respect to the sequence $\{\eta_i\}$ of the quality index and, according to Proposition 3, we conclude that a monopoly will prefer to supply only the higher quality of seeds. Knowing that the seed unit cost represents roughly six percent[6] of the total cost, the cost $c_z * \alpha/\gamma$ of other inputs was evaluated to 722€/q. The mean of the random term ϵ_0, μ_0, is normalised to 1 and μ_i is worked out through a ratio of the amount of seeds required to sow one hectare with farm-saved seeds and certified seeds, here $\frac{1.4}{1.3} = 1.076$. Parameter σ_0 and σ_i were set so as to obtain realistic prices for breeders varieties in our simulations. σ_i is lower than σ_0 because of the homogeneity and stability criteria. There are 356,070 farmers in France with an average acreage of 14.42 hectares of land allocated to wheat[7]. This information allows us to calculate the market size ($L_{mean} * M_{farmers} * numbers\ of\ seeds\ by\ hectares$). Finally, based on Brink and McCarl (1978) and

[6] According to FADN database.

[7] The FADN only takes professional farmers into account, for more information visit `http://ec.europa.eu/agriculture/rica/`, last accessed June 2014.

Saha (1997), we set the risk aversion parameter θ to 0.25.

3.3 Numerical Results

Prior presenting the results of our numerical simulations, it is worth recalling the main policy options. The PBRs system leads to an oligopoly with Bertrand-Nash equilibrium while the patent system gives a monopoly position to one breeder. An alternative to varieties created by breeders consists in buying landrace seeds, which are priced at their unit cost. In order to remedy to information asymmetries about the quality of seeds, two kind of commercialisation rules are considered: minimum standards or a catalogue. Registration in the catalogue requires to pass the DUS and VCU tests. Landrace seeds can succeed in passing these tests only at an additional unit cost. In counterpart, if they meet these criteria, the uncertainty surrounding the performance of landrace seeds is lowered to the same level than the one characterising seeds of the breeders varieties. Crossing the different criteria generates four cases. Firstly, a "European case" with PBRs-catalogue rules. In contrast, there is a "US case" with Patent-minimum standards rules. The two other possibilities are a PBR-standards minimum case and a patent-catalogue case. These four cases, which somewhat simplifies the reality (a PBRs system and a patent system can make together) give an idea of the impact of regulation in the seed industry.

Note that, given the values of parameters reported in Table 1, some farmers will have a negative profit and will prefer not to grow wheat. Two reasons can explain this result: subsides provided by public authorities in the context of the Common Agricultural Policy are disregarded and only a part of farmers output, and thus of profit, is computed. Indeed, farmers with a low yield are mostly not specialised in cereals.

With only one breeder variety that compete with the landrace (i.e. with $N = 1$), results for the PBRs system and the Patent system are similar whatever the rule for commercialisation of seeds. Recall that the profit for suppliers of the landrace amounts to zero because this market segment constitutes a competitive fringe for the monopoly breeder that supplies variety 1 (see Table 2). In the catalogue case the seed market splits into roughly 45% for the landrace seeds and 55% for the "breeder" seeds. In comparison, the monopolist, in the minimum standards case , supplies only 47% of the seed market. The difference is due to a higher ratio between the price of the breeder variety and the price of the landrace variety in the minimum standards case (2.43584) than in the catalogue case (1.85774). Biodiversity, as measured by the Simpson index, is slightly higher with minimum standards than with a catalogue rule, but it seems that the result is highly sensitive to the values of parameters. Unsurprisingly, the price of seeds for the breeder variety and the profit of the breeder are higher for the catalogue case than for minimum standards case whereas the risk-adjusted profit of farmers is lower. The net effect produces a higher total welfare in the minimum standards case.

Table 2: Results with one "breeder" seed

	Minimum standards		Catalogue	
Varieties	landrace	breeder 1	landrace	breeder 1
μ_i	1	1.04	1	1.04
w_i (€/quintal)	31.25	76.12	40.56	76.8
q_i (thousand)	3752	3435	3222	3966
π_i (million)	.	90	.	106.9
$A_{min}(E)$	26.5		26.4	
$threshold_2$	73.5		66.7	
$A_{max}(E)$	116.5		116.4	
$\pi_{farmers}$ (euros)	3727		3445	
$Welfare$ (billion)	1.346		1334	
E^a	0.499		0.494	

[a] E means Simpson index of diversity

With two breeder varieties (i.e. with $N = 2$), the four cases appear because of dissociation between the PBR and the patent system (see Table 3). With the oligopolistic market structure favoured by the PBRs system, the incremental innovation (variety 2) induces a decrease of the price of variety 1 compared to the case $N = 1$ whereas this variety is no longer supplied under the patent regime (see Proposition 3). In accordance with Proposition 8, the price of the variety 2 is higher in the patent system than in the PBRs system, whatever the commercial rule that is in force.

Comparing the European case with the American case, we notice that the US system is better for breeders who will have a higher profit than in the context of European rules. Regarding farmers, the EU system seems preferable because the conjunction of competition between breeders, that is allowed with the PBRs system, and sequential innovation pushes prices down for variety 1. Nevertheless, the total welfare is lower in the European context because higher risk adjusted profits for farmers do not counterbalance the lower profits of breeders. The Simpson biodiversity index is slightly higher in the US system in spite of the absence of variety 1. This results clearly emphasises that measuring biodiversity as a simple count of varieties grown by farmers may be misleading and that the concentration of market shares matters.

Looking at the four cases all together, the maximum profit that a breeder can earn is found in the patent-catalogue case thanks to higher prices whereas the PBR-standards situation is the best for farmers due to lower prices of the seeds of both breeder varieties and the landrace variety. As a consequence, the best situation for total welfare is found in the PBR-standards case. By contrast, the value of the Simpson biodiversity index is far from being the highest in the PBR-standards case. This finding shows that although higher competition lowers market concentration, it does not systematically enhance biodiversity in spite of the strong link between the two concepts when biodiversity is measured by the Simpson index. Our simulations indicate that, in a static framework, strengthening competition thanks to PBRs in place of patents may lower the price of the highest quality of seeds more drastically than it does for other qualities of seeds, which induces a concentration of the market in favour of the two polar qualities (the highest quality of seeds and landrace seeds) but at the detriment of biodiversity. More generally, our simulation results stress that *ceteris paribus* (i.e. for unchanged commercialisation rules) PBRs do not promote biodiversity compared to a patent regime, at least in a static framework. Conversely, *ceteris paribus* (i.e. for an unchanged IPRs regime) minimum standards in place of a catalogue commercialisation rule is more efficient at promoting biodiversity. Nevertheless the story can substantially differ if we consider incentives to invest in R&D in a dynamic framework.

Table 3: Results with two "breeder" seeds

	Oligopoly+Catologue ("European" case)			Monopoly+Catalogue		
Varieties	landrace	breeder 1	breeder 2	landrace	breeder 1	breeder 2
μ_i	1	1.04	1.08	1	1.04	1.08
w_i (€/quintal)	40.54	56.16	84.39	40.54	75.35	108.31
q_i (thousand)	249	1857	5082	2888	0	4301
π_i (million)	.	12	176	.	0	251
$A_{min}(E)$	25.6			26.2		
$threshold_2$	28.7			.		
$threshold_3$	52			62.4		
$A_{max}(E)$	115.6			116.2		
$\pi_{farmers}$ (euros)	3789			3601		
$Welfare$ (billion)	1.536			1.534		
E^a	0.432			0.481		
	Oligopoly+Standards			Monopoly+Standards ("US" case)		
Seeds	landrace	breeder 1	breeder 2	landrace	breeder 1	breeder 2
μ_i	1	1.04	1.08	1	1.04	1.08
w_i (€/quintal)	31.25	54.42	83.66	31.25	74.46	107.7
q_i (thousand)	942	1271	4974	3183	0	4005
π_i (million)	.	6	168	.	0	232
$A_{min}(E)$	26.1			26.4		
$threshold_2$	37.9			.		
$threshold_3$	53.9			66.3		
$A_{max}(E)$	116.1			116.4		
$\pi_{farmers}$ (euros)	3966			3707		
$Welfare$ (billion)	1.586			1.552		
E^a	0.473			0.493		

[a] E means Simpson index of diversity

4 Endogenous innovation in a dynamic framework

PBRs aim at generating higher incentives than patents in favour of variety creation through incremental inventions. A comprehensive analysis of the respective merits of PBRs and patents thus requires to extend the static analysis presented so far to a dynamic framework. For this purpose, we consider a two periods model. Market equilibrium at each period is determined in accordance with the static analysis presented above but the number of varieties is endogenous. For a new variety to be available, breeders have to invest a sunk cost in R&D and the outcome of the innovation process is uncertain. This section examines how the incentives to participate to the innovation race and the outcome of the innovation race at the two periods are affected by the IPRs system and the commercialisation rules in force. The problem is solved backwards, starting first with the incremental invention at the second period and then proceeding with the initial, drastic, invention at period one.

4.1 Incentives for an incremental invention

4.1.1 Incentives with a patent system

According to the calibration of the model presented in Table 1 and Proposition 3, we know that a monopolist will always choose to supply only the highest quality variety. Moreover, a patent regime confers the exclusivity of the opportunity to research and develop the incremental variety to the breeder of the initial variety. Hence, the breeder of the initial variety will engage in R&D in order to obtain the second variety characterised by a higher quality if and only if

$$(\Lambda v_2^{mon} + (1 - \Lambda) v_1^{mon}) - FC > v_1^{mon} \tag{22}$$

where Λ is the probability of success, FC is the fixed cost of R&D, v_1^{mon} is the flow of profit for the monopolist with variety 1 whereas $v_2^{mon} > v_1^{mon}$ is the flow of profit for the monopolist with variety 2. The left-hand of equation (22) represents what earns the breeder if he innovates minus its fixed cost of R&D and the right-hand represents what he earns if it does not innovate. Equation (22) simplifies as follows

$$\Lambda(v_2^{mon} - v_1^{mon}) > FC \tag{23}$$

where the left-hand is the expected gross benefit of the breeder that accrues from an engagement in R&D and the right-hand is the associated cost. According to the calibration presented in Table 1, the increment $v_2^{mon} - v_1^{mon}$ in profit flows is slightly higher with a catalogue (144.1) than with minimum standards (142).

4.1.2 Incentives with a PBRs system

Under a PBRs system, either the incumbent breeder that already supplies variety $n = 1$ or a new breeder are able to invest in a R&D program that aims at obtaining the higher quality variety $n = 2$ at period 2. An innovation race occurs if the two breeders decide to engage in R&D. This innovation race has two opposite effects. On the one hand, it increases the probability of the availability of the second variety at period 2. This probability is given by $\Lambda(1-\Lambda) + (1-\Lambda)\Lambda + \Lambda^2$ and increases from zero to one for $\Lambda \in [0, 1]$. Indeed, with probability $\Lambda(1-\Lambda)$, the R&D program of the incumbent breeder is the only one to succeed, with probability $(1-\Lambda)\Lambda$ the R&D program of the new breeder is the only one to succeed and, finally, with probability Λ^2 both programs succeed. On the other hand, as stresses the last term in the expression of the probability that variety $n = 2$ is available in period 2, there is a risk of an inefficient duplication of the R&D investment cost FC. In this last case, the rights on the second variety are assumed to be randomly affected to one of the two breeders.

Table 4: The matrix of the game for the incremental invention

	Incumbent R&D	Incumbent no R&D
Entrant R&D	V_1^E \ V_1^I	V_2^E \ V_2^I
Entrant no R&D	V_3^E \ V_3^I	V_4^E \ V_4^I

Depending on the decision of each breeder to engage in R&D, four situations may arise. These situations, referred to as situation s_1 to s_4, correspond to the four cells in Table 4. $V^I_{s_i}$ and $V^E_{s_i}$ respectively denote the expected flow of profit of the incumbent breeder and of the entrant in situation s_i. The first situation (s_1) correspond to an engagement of both breeders in R&D. The entrant then competes to obtain the flow of profit v_2^{oli} generated by the supply of variety $n = 2$ given that varieties 1 and 2 are supplied in an oligopolistic market structure. Accordingly, we have

$$V^E_1 = (1 - \Lambda)^2 0 + \Lambda(1 - \Lambda)0 + (1 - \Lambda)\Lambda\ v_2^{oli} + \Lambda^2(\frac{1}{2}v_2^{oli} + \frac{1}{2}0) - FC \tag{24}$$

For his part, the incumbent can switch to a monopolistic position with variety $n = 2$ if he wins the innovation race, or switch to an oligopolistic position where he supplies the lower quality variety $n = 1$ if the entrant wins the innovation race, or stay on a monopolistic position if neither him nor the new breeder succeed in obtaining variety $n = 2$. Thus, we have

$$\begin{aligned} V^I_1 =& (1 - \Lambda)^2 v_1^{mon} + \Lambda(1 - \Lambda)v_2^{mon} + (1 - \Lambda)\Lambda v_2^{oli} \\ &+ \Lambda^2(\frac{1}{2}v_1^{oli} + \frac{1}{2}v_2^{mon}) - FC \end{aligned} \tag{25}$$

Where v_1^{oli} stands for the flow of profit generated by the supply of variety $n = 1$ given that varieties 1 and 2 are supplied in an oligopolistic market structure.Following the same logic, we obtain that

$$V^E_2 = \Lambda v_2^{oli} + (1 - \Lambda)0 - FC \tag{26}$$

$$V^I_2 = \Lambda v_1^{oli} + (1 - \Lambda)v_1^{mon} - FC \tag{27}$$

and

$$V^E_3 = 0 \tag{28}$$

$$V^I_3 = \Lambda v_2^{mon} + (1 - \Lambda)v_1^{mon} - FC \tag{29}$$

Finally, the last situation (s_4) is the simplest and is characterised by

$$V_4^E = 0 \tag{30}$$

$$V_4^I = v_1^{mon} \tag{31}$$

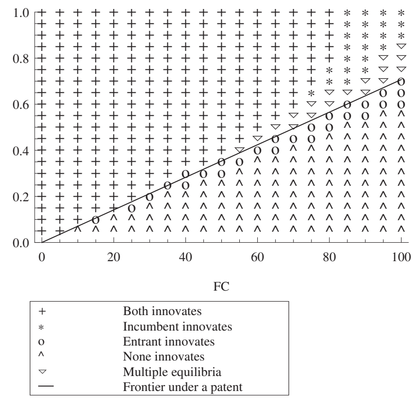
The outcome of the Nash game for the incremental invention described in Table 4 crucially depends on the value of the different parameters. We make a special emphasis on the sensitivity analysis with respect to the parameters Λ and FC that are specific to the dynamic framework.

4.1.3 Outcome of the game for an incremental variety

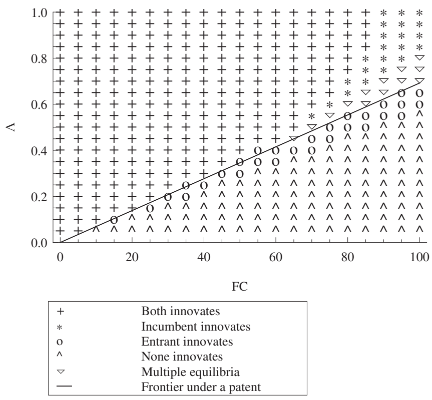
Using the numerical results of section 4.3, the Nash equilibrium that emerges with a PBRs system from the four strategic decisions presented in Table 4 are determined for different values of Λ on the range $]0, 1]$ and different values of the fixed R&D cost on the range $]0, 100]$. Results are showed in figure 3. Multiple equilibria are possible. In such an event, either only the incumbent invests or only the entrant invests but there is an indeterminacy of who exactly invest. Figure 3 also presents the frontier above which incentives to innovate under a patent regime are sufficient for the incumbent to invest at period 2. This frontier is defined by the inequality (23).

The two Nash equilibria that more commonly occur are situations s_1 and s_4. The first situation is characteristic of a high probability of success and low R&D costs whereas the second situation occurs in the opposite context. Unsurprisingly, situation s_1 emerges as a Nash equilibrium for combinations of Λ and FC above the frontier associated to the patent regime and conversely for situation s_4. Situation s_3 where the incumbent breeder is the only one that engage in R&D emerges as a Nash equilibrium for a high probability of success and a high R&D cost that would justify engagement in R&D under a patent regime. Multiple equilibria occur when the probability of success is slightly lower compared to those cases where s_3 is the sole Nash equilibrium. As regards the impact of commercialisation rules,

Figure 3: Nash equilibria and innovation frontiers



(a) Minimum standards

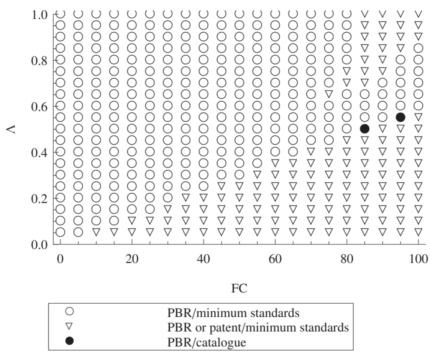


(b) Catalogue

the choice between minimum standards on the one hand and a catalogue on the other hand seems to have a limited impact on the outcome of the innovation game. Situations where both breeders innovate are slightly more abundant in the catalogue case. Interestingly, Figure 3 exhibits cases where the entrant is the only one to engage in a R&D program under a PBRs regime (situation s_2 in Table 4), whereas the incumbent chooses not to invest under patent regime. In this sense, PBRs better promote incremental innovation compared to patents.

The optimal choice of the type of IPRs used to protect variety creation and of the type of commercial rules has been computed for each combination of values of Λ and FC given the outcome of the Nash game reported in Table 4. This optimal choice has to be understood as the outcome of a Stackelberg game. Indeed, breeders decide to invest or not in a R&D program and choose their price given the IPRs regime and the commercialisation rule set by the public regulator. Given the optimal response of breeders, the public regulator chooses the combination of IPRs and commercialisation rule that maximises the total surplus. Figure 4 indicates what is this optimal pair of IPRs and commercialisation rule the public regulator should choose at period 2. Only three pair of rules are present: PBRs with minimum standards, PBRs (or indifferently patents) with minimum standards and, finally, PBRs coupled with a catalogue.

Figure 4: Optimal choice of IPRs and commercial rules at period 2 for the public regulator



The more effective pair of rules regarding the optimal welfare seems to be the coupling of PBRs with minimum standards even if, for some rare combinations of Λ and FC, a catalogue is preferable for commercial rules. The point is that patents never emerge as an optimal system of IPRs for the public regulator or, at least, never strictly dominates PBRs. The optimal coupling of PBRs with minimum standards is the most represented in our results over the different levels of the sunk R&D cost and of the probability of success. Moreover, even if there is no competition (only the incumbent invests) a PBRs system provides a total welfare similar to that provided by a patent system. More surprisingly, for some pair of parameters, the catalogue rule coupled with PBRs provides a higher total welfare than minimum standards coupled with PBRs. Such a result more specifically arises along the frontier above which a monopolist would engage in R&D under a patent regime. The reason for this is that a catalogue may rise profit flows compared to minimum standards and, consequently, may favour the obtention of the new plant variety.

4.2 Incentives for a radical invention

When turning to the decision of breeders to engage in R&D for the initial drastic invention at period 1 (obtention of variety $n = 1$), two important differences arises compared to the decision to engage in R&D for the increment invention at period 2 (obtention of variety $n = 2$). The first difference is the symmetric position of each of the two breeders. The second difference is that expected profit flows of the two consecutive periods have to be accounted for when determining the monetary incentives to engage in R&D at period 1. Assuming that the sunk cost of R&D is similar at the two periods, the expected discounted sum of profit flows associated with the R&D investment at period one under a patent regime amounts to

$$\begin{aligned} V_{patents} =&(1-\Lambda)^2(Max\{\frac{(1-\Lambda)\Lambda v_1^{mon} + \frac{\Lambda^2}{2} v_1^{mon} - FC}{1+r};0\}) \\ &+((1-\Lambda)\Lambda + \frac{\Lambda^2}{2}) \\ &* (v_1^{mon} + \frac{Max\{(1-\Lambda)v_1^{mon} + \Lambda v_2^{mon} - FC\ ;\ v_1^{mon}\}}{1+r}) - FC \end{aligned} \tag{32}$$

where r is the discount rate. Indeed, if none of the two breeders succeeds in obtaining the first variety $n=1$ at period 1 (probability $(1-\Lambda)^2$), a new innovation race occurs at period 2 for the same variety and generates a profit flow v_1^{mon} at period 2 if the breeder wins the race. If the breeder is the only one to succeeds in period 1 (probability $(1-\Lambda)\Lambda$) or if the two breeders succeeds in period 1 but the patent is randomly allocated to the breeder (probability $\Lambda^2/2$ to succeed and to be granted the property right), then the profit flow is received at period 1 and is augmented by the discounted net profit flow associated with the optimal decision to engage in R&D in order to obtain variety $n=2$ or not at period 2.

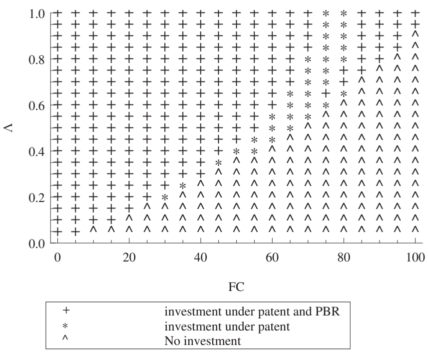
Under a PBRs regime, the equivalent to (32) is given by

$$\begin{aligned} V_{PBRs} =&(1-\Lambda)^2(Max\{\frac{(1-\Lambda)\Lambda v_1^{mon} + \Lambda^2 \frac{1}{2} v_1^{mon} - FC}{1+r};0\}) \\ &+\Lambda(1-\Lambda)\frac{V^E_{Nash}}{1+r} + (1-\Lambda)\Lambda(v_1^{mon} + \frac{V^I_{Nash}}{1+r}) \\ &+\Lambda^2(\frac{1}{2}(v_1^{mon} + \frac{V^I_{Nash}}{1+r}) + \frac{1}{2}\frac{V^E_{Nash}}{1+r}) - FC \end{aligned} \tag{33}$$

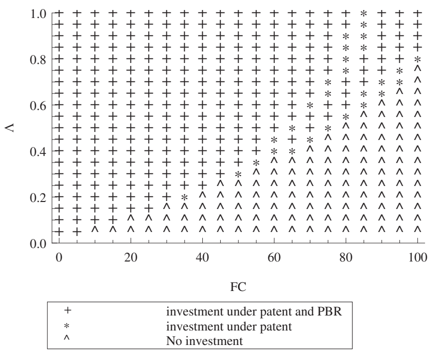
where V^I_{Nash} (respectively V^E_{Nash}) stands for the expected profit flow of the incumbent breeder (respectively the entrant) at period 2 given the outcome of the Nash equilibrium of the innovation game for obtaining variety $n = 2$.

We have to rely on numerical results in order to assess which combination of IPRs and commercialisation rules yields the higher expected and discounted sum of total surplus in an intertemporal perspective and may thus be chosen by the public regulator. Figure 5 and 6 synthesises the result in function of the probability Λ of success of R&D programs and of the sunk cost FC of R&D, under the assumption that the discount rate from period 1 to period 2 amounts to 10%. Such a discount rate may seem rather high but actually applies to the lapse of time required to develop the incremental variety generally exceeds one year.

Figure 5: Innovation at period 1



(a) Minimum standards



(b) Catalogue

Figure 6: Optimal choice of IPRs and commercial rules at period 1 for a public regulator

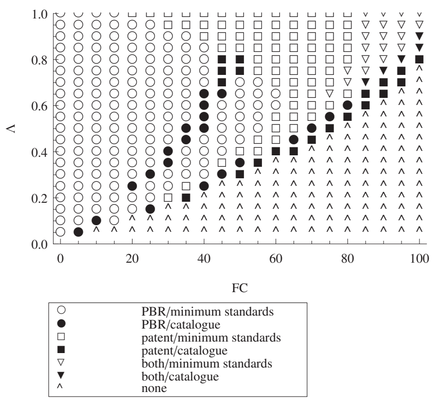


Figure 5 shows that it is more often optimal not to invest in the obtention of the initial variety with minimum standards than with a catalogue. This result is expected because minimum standards strengthen the threat on monopolistic rents and consequently reduce the monetary incentives to invest in R&D. For a limited subset of the space $\{FC, \Lambda\}$, a patent regime is required for innovation to occur at period 1. Such situations are encountered when both the R&D sunk cost FC and the probability Λ of R&D success are high, or at the limit with the area for which investing in R&D to obtain the initial breeder variety is not optimal. In such cases, it is optimal for the public regulator to avoid replication of R&D sunk costs in order to ensure that investment occurs, which is obtained by granting stronger property rights in the form of patents rather PBRs. Note that for higher values of FC and Λ (on the right and top of the Figure), innovation occurs whether IPRs correspond to PBRs or patents because, at period 2, PBRs and patents are equivalent (only the incumbent invests at period 2). The combination of IPRs regime and commercialisation rule that a public regulator should use is illustrated by Figure 6. Below an ascendant diagonal in space $\{FC, \Lambda\}$, none of the four possible combinations will create enough incentives for investing in the obtention of the initial breeder variety. Above this frontier, there is a clear distinction between an area where PBRs have to be preferred to patents and conversely. Roughly speaking, PBRs are optimal from the view point of the regulator when FC is inferior to a parabolic expression of Λ. The parabolic form results form the requirement that Λ has to be sufficiently high to make sure investment will occur at periods 1 and 2 with PBRs but not too high so that the probability Λ^2 of an inefficient duplication of R&D investment does not increase too much and does not justifies adopting patents rather than PBRs to avoid the negative impact of this replication on the total surplus. Results as regards commercialisation rules are less clear. A catalogue rule may be optimal close to the frontier under which investing at period 1 is never optimal. The catalogue is then used in combination with patents to enhance the amount of rents that accrue to the monopolistic breeder and create enough monetary incentives to innovate. More surprisingly, a catalogue may be chosen by the regulator in combination with either PBRs or patents along a thick ray that split the area where a combination of PBRs and minimum standards dominates. A decomposition of the simulation results indicates that this is due to the Max term in the first line of equations (32) and (33) which yields the expected profit of a breeder associated to R&D investment at period 2 when none of the R&D programs has succeeded at period 1. For a fixed value FC of sunk costs of R&D, this maximum will be strictly positive if and only if Λ is sufficiently close to one. If Λ is not sufficiently close to one, a switch from minimum standards to a catalogue increases v_1^{mon} and limits the risk of non innovation at all on the two periods. The highest the value of FC the highest the risk of no innovation at all on the two periods. Therefore, an increase in FC may justify to switch from PBRs to patents in addition to the switch from minimum standards to a catalogue. With this respect, our simulation results are consistent with the conclusion set by Moschini and Yerokhin (2008); Yerokhin and Moschini (2008). A noticeable point that is highlighted by Figure 6 is that our simulations results support the coupling of PBRs and minimum standards which encountered neither in the US nor in Europe when sunk costs of R&D FC are low and the coupling of patents and minimum standards when these sunk costs are high. This latter case more or less corresponds to the solution adopted in the US. By contrast, the solution adopted in Europe (i.e. a coupling of PBRs and a catalogue) is supported by our simulation results only in few specific cases. Such a result is all the more striking that the model is calibrated in French data for wheat.

5 Conclusion

The dynamic vertical differentiation model developed in this article to tackle with both the problem of asymmetric information and the problem of a lack of incentives to innovate on the seed market, in connection with the role of biodiversity as a public good subject to under-provision, suggests that the combination of IPRs regime and commercialisation rule that a public regulator may choose to maximise the expected and discounted total surplus crucially depends on the level of sunk R&D costs and on the probability of R&D success.

Numerical simulations obtained with a calibration of the model for wheat in France more or less confirm the intuitive idea that PBRs combined to minimum standards have to be preferred when sunk costs of

R&D are low or medium and the probability of R&D success is sufficiently high to justify investment in R&D programs. Otherwise, patents combined with minimum standards have to be preferred, except in some peculiar cases where patents may preferably be coupled with a catalogue. Though calibrated on French data, our model thus only weakly supports the coupling of PBRs and a catalogue adopted in Europe. Our simulation results better support the coupling of patents and minimum standards that may be considered as close to the solution adopted in the US or, even, the novel solution consisting in coupling PBRs and minimum standards.

A result for the model developed in this article has not yet been discussed. According to the model, landrace seeds are chosen by non-productive farms (farms with a small productive parameter A), while industrial seeds are chosen by all other farmers. We can see that the wide difference in terms of intellectual property rights on plants between developing countries and developed countries may be because the average farm size is very different between the two kinds of countries. Developing countries still have many low productive farms for which there is a large production of farm-saved seeds while farmers in developed countries are pushed to buy industrial seeds. The modelling also gives this result because it is difficult for non-productive farms to pay high industrial seed prices. Furthermore, it would be interesting to try this model with crops other than the wheat in order to see if the consequences of the catalogue and the choice of the intellectual property right system on this model would be similar.

A Comparative statics of oligopoly prices with respect to c_0 and σ_0 when $N = 2$

Substituting c_0 for w_0, the reaction functions for the Bertrand-Nash game in prices are given by:

$$w_1 = \frac{c_1}{2} + \frac{w_2}{2}\frac{(\mu_1 - \theta\sigma_1) - (\mu_0 - \theta\sigma_0)}{(\mu_2 - \theta\sigma_2) - (\mu_0 - \theta\sigma_0)} + \frac{c_0}{2}\frac{(\mu_2 - \theta\sigma_2) - (\mu_1 - \theta\sigma_1)}{(\mu_2 - \theta\sigma_2)(\mu_0 - \theta\sigma_0)} \tag{34}$$

$$w_2 = P\ \alpha\frac{(\mu_2 - \theta\sigma_2)(\mu_1 - \theta\sigma_1)}{2}A_{\max} + \frac{c_2}{2} + \frac{w_1}{2} \tag{35}$$

We differentiate the two reaction functions with respect to c_0 and w_0 in the neighborough of the equilibrium:

$$dw_1 = \frac{\partial w_1}{\partial c_0} dc_0 + \frac{\partial w_1}{\partial \sigma_0} d\sigma_0 + \frac{\partial w_1}{\partial w_2} dw_2 \tag{36}$$

$$dw_2 = 0dc_0 + 0d\sigma_0 + \frac{1}{2} dw_1 \tag{37}$$

The second relation just states that variations of w_2 are half those of w_1. Moreover, given that μ_i increases with i whereas σ_i decreases with i, one easily checks that in the above equations we have

$$\frac{\partial w_1}{\partial w_2} = \frac{1}{2} \frac{(\mu_1 - \theta\sigma_1) - (\mu_0 - \theta\sigma_0)}{(\mu_2 - \theta\sigma_2) - (\mu_0 - \theta\sigma_0)} \in [0, \frac{1}{2}] \tag{38}$$

$$\frac{\partial w_1}{\partial c_0} = \frac{(\mu_2 - \theta\sigma_2) - (\mu_1 - \theta\sigma_1)}{2(\mu_2 - \theta\sigma_2) - (\mu_0 - \theta\sigma_0)} \in [0, \frac{1}{2}] \tag{39}$$

$$\frac{\partial w_1}{\partial \sigma_0} = \theta(\frac{w_2 + c_0}{2}) \frac{(\mu_2 - \theta\sigma_2) - (\mu_1 - \theta\sigma_1)}{((\mu_2 - \theta\sigma_2) - (\mu_0 - \theta\sigma_0))^2} > 0 \tag{40}$$

We conclude that $\frac{dw_1}{dc_0} > 0$ and $\frac{dw_1}{d\sigma_0} > 0$ so that, in the neighborough of $\{\sigma_0, c_0\}$ we have the same type of isoprice curves than under a patent regime. As the demand system is the same under a PBRs system and a patent regime, we also conclude that in the neighborough of $\{\sigma_0, c_0\}$ the isoquant curves are of the same type than under a patent regime..

B Isoprofit equation for the first "breeder" variety

As we highlighted in section 3.2.1 the unit cost has to be a convex function of the quality in order to obtain a multi-product monopoly. We examine the isoprofit of the first "breeder" variety to look at consequences of this convexity or this non-convexity.

$$v_1 = (w_1^* - c_1)q_1 \tag{41}$$

where $q_1 = \left(\frac{w_2 - w_1}{P\alpha(\eta_2 - \eta_1)} - \frac{w_1 - w_0}{P\alpha(\eta_1 - \eta_0)}\right) * \frac{M * L * \frac{1}{\alpha}}{A_{max} - A_{min}}$

To construct the figure 2 we rearrange the profit equation and we obtain the isoprofit equation

$$w_2 = w_1 + w_1 \frac{\eta_2 - \eta_1}{\eta_1 - \eta_0} - w_0 \frac{\eta_2 - \eta_1}{\eta_1 - \eta_0} + v_1 \frac{P\alpha(\eta_2 - \eta_1)}{w_1 - c_1} \frac{A_{max} - A_{min}}{M * L * \frac{1}{\alpha}} \tag{42}$$

The first and the second degree of partial derivatives of the isoprofit is analysed to determine the isoprofit curve shape

$$\frac{\partial w_2}{\partial w_1} = 1 + \frac{\eta_2 - \eta_1}{\eta_1 - \eta_0} - v_1 \frac{P\alpha(\eta_2 - \eta_1)}{(w_1 - c_1)^2} \frac{A_{max} - A_{min}}{M * L * \frac{1}{\alpha}} \tag{43}$$

$$\frac{\partial^2 w_2}{\partial w_1^2} = +2v_1 \frac{P\alpha(\eta_2 - \eta_1)}{(w_1 - c_1)^3} \frac{A_{max} - A_{min}}{M * L * \frac{1}{\alpha}} \tag{44}$$

The first-degree is negative and the second-degree is positive, thus the isoprofit curve is convex when the monopoly is multi-product (as figure 2 in section 3.2.3).

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